NASA / SwRI / MSSS / Gerald Eichstädt / Seán Doran

Initial Operations Experience and Results from the Juno Gravity Experiment

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Overview

Agenda

1. What is Gravity Science?
2. Instrumentation
3. Juno Mission to Jupiter
4. Current Operations Status
5. Dynamics at Jupiter
6. Initial Results

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Measuring the Gravity Field

$$E_0 = mgh_0 + \frac{1}{2}mv_0^2$$

$$E_f = mgh_f + \frac{1}{2}mv_f^2$$

$$f = \left(1 + \frac{\Delta v}{c}\right) f_0$$

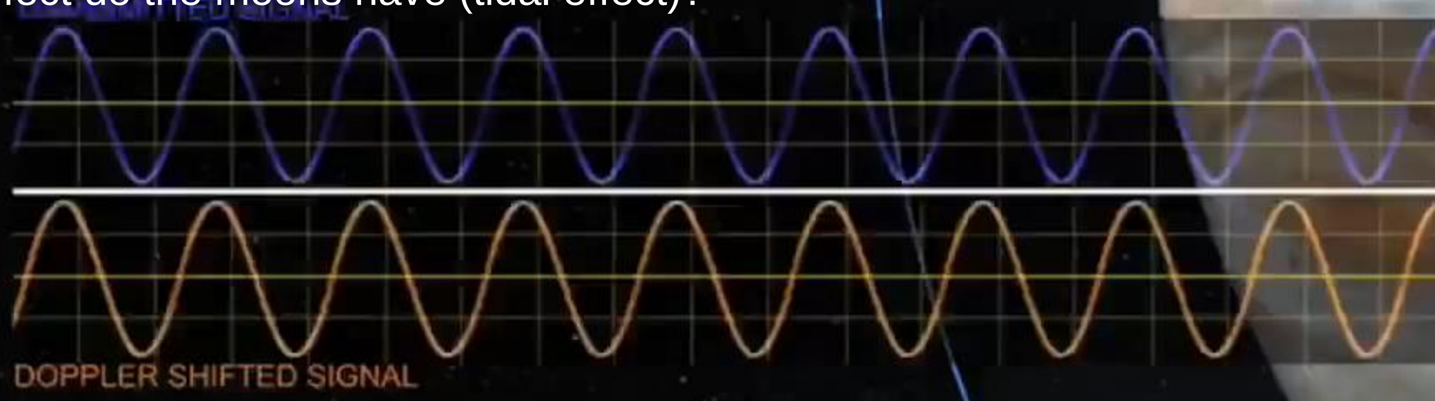
$$\Delta v = c\,\frac{\Delta f}{f_0}$$

$$v = \sqrt{2g\Delta h}$$

$$g = \frac{c^2 \Delta h}{2}\left(\frac{\Delta f}{f_0}\right)^2$$

Gravity Science

- Examine changes in phase/**frequency** between the ground-based receiving stations of the NASA Deep Space Network and the Juno spacecraft to determine:
  - – Mass/density
  - – Spherical harmonics (gravitational field)
    - Lower-degree terms: oblateness, rotational axis, deep interior structure
      - – Is there a core?
      - – How deep are the winds (differential rotation)?
      - – What effect do the moons have (tidal effect)?



Asmar, Bolton, Buccino, et al, *The Juno Gravity Science Instrument*, Space Science Reviews 213, 2017

https://www.youtube.com/watch?v=ulzq_mlU-fA

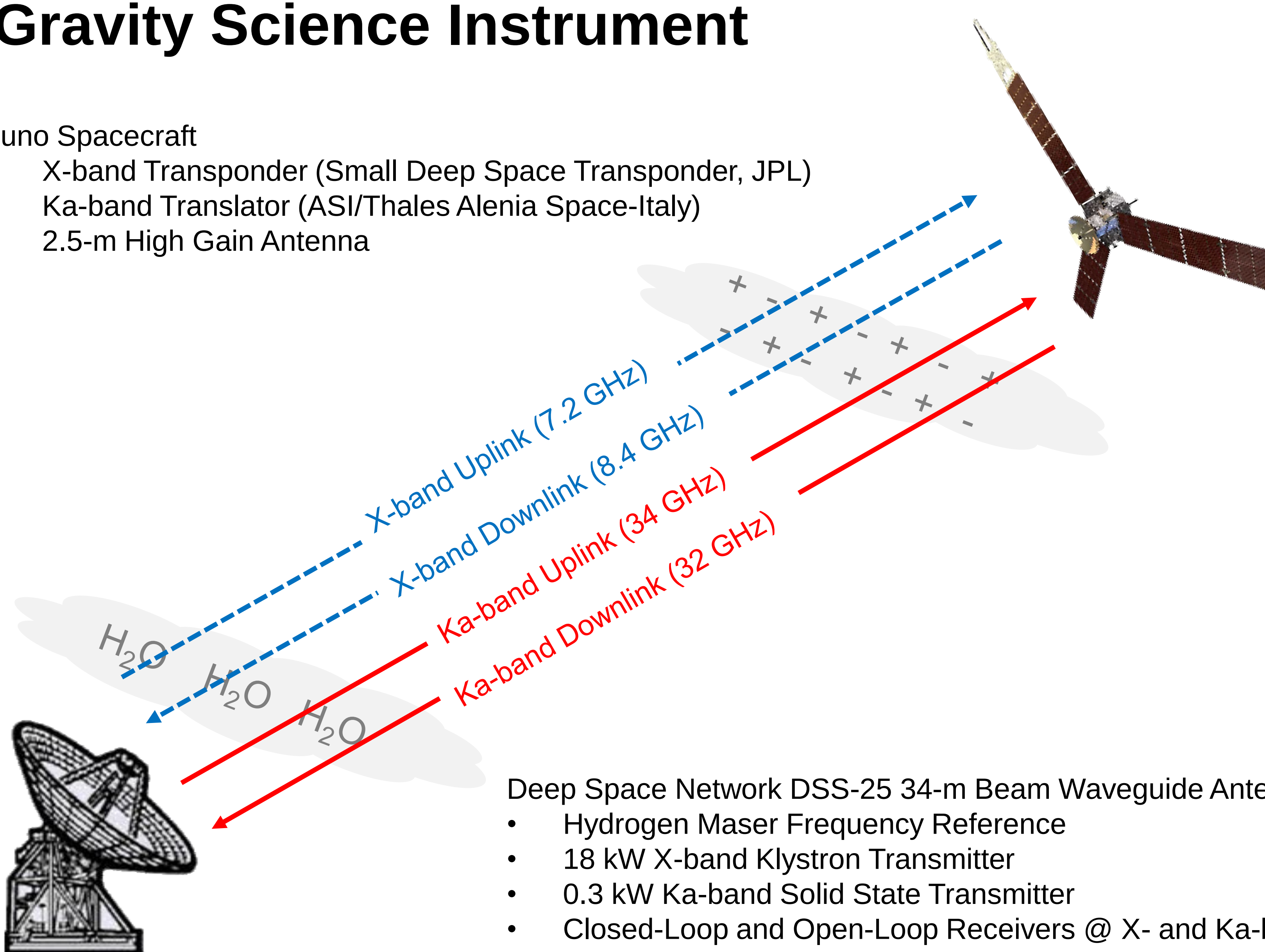
Juno Mission

- First outer-planet solar powered mission
- 53-day polar elliptical orbit designed to minimize radiation exposure
  - Launch: August 2011 (5 year cruise)
  - Orbit Insertion: July 2016
- Suite of ten science instruments to investigate Jupiter's:
  - Interior
  - Atmosphere
  - Magnetosphere

Bolton, et al, *The Juno Mission*, Space Science Reviews 213, 2017

Gravity Science Instrument

Juno Spacecraft
- X-band Transponder (Small Deep Space Transponder, JPL)
- Ka-band Translator (ASI/Thales Alenia Space-Italy)
- 2.5-m High Gain Antenna



Deep Space Network DSS-25 34-m Beam Waveguide Antenna
- Hydrogen Maser Frequency Reference
- 18 kW X-band Klystron Transmitter
- 0.3 kW Ka-band Solid State Transmitter
- Closed-Loop and Open-Loop Receivers @ X- and Ka-band
- Advanced Water Vapor Radiometers

Asmar, Bolton, Buccino, et al, *The Juno Gravity Science Instrument*, Space Science Reviews 213, 2017

Unique Upgrades to DSS-25

Ka-band Transmitter

- Inherited 800 W Klystron from Cassini
- Failed twice; replaced with dual combined SSPA for 300 W after launch

Adv. Water Vapor Radiometer

- Measures sky brightness temperatures at 22.2, 23.8, and 31.4 GHz

Noise Sources

Earth Troposphere

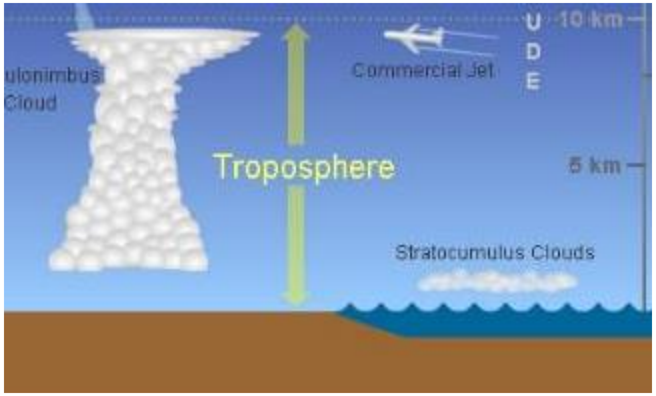


Image courtesy UCAR

Earth Ionosphere*

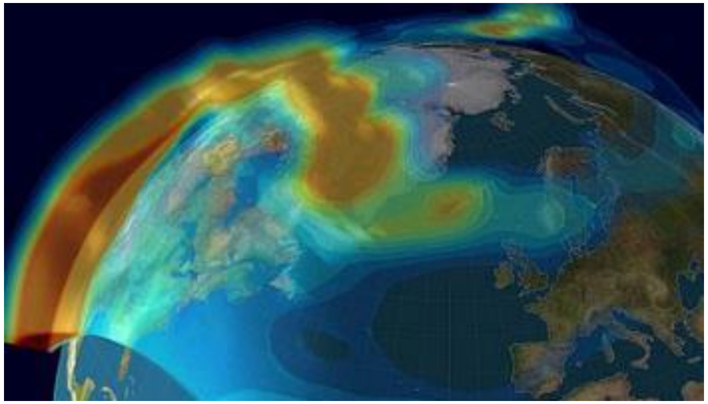


Image courtesy Universe Today

Solar Plasma*

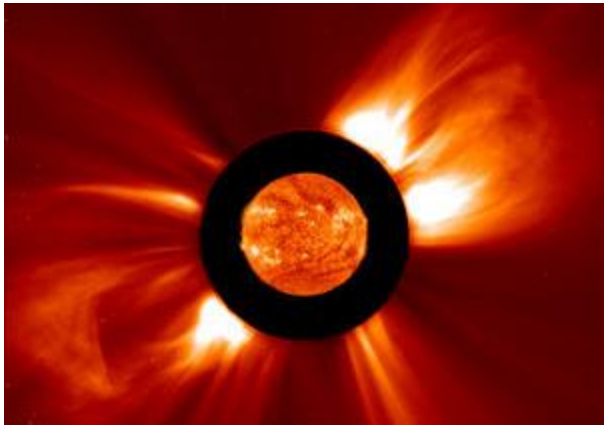


Image courtesy NASA APOD

Io Plasma Torus*

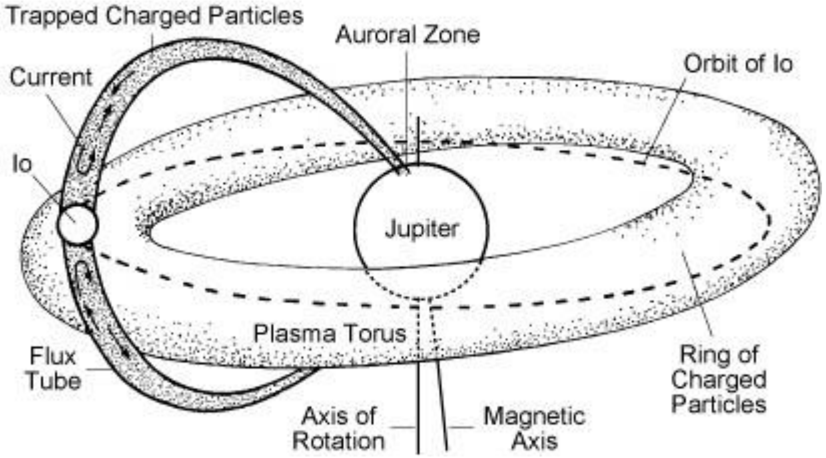
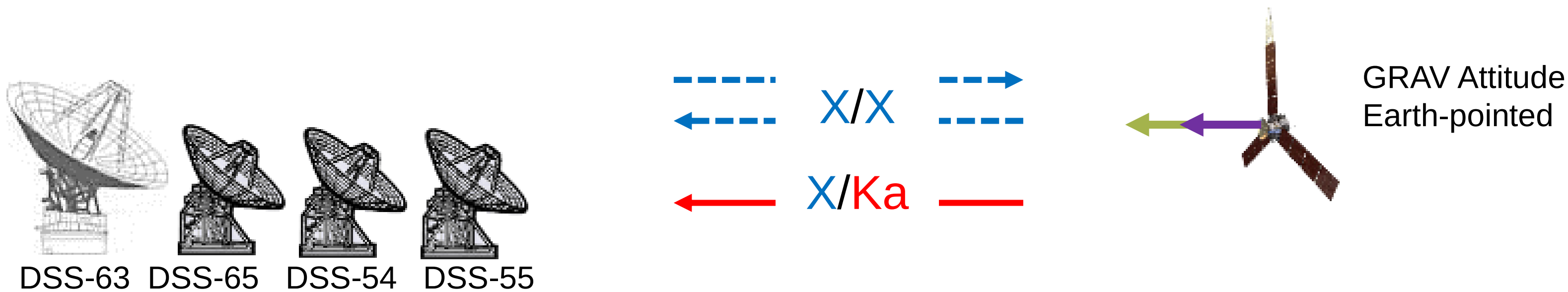


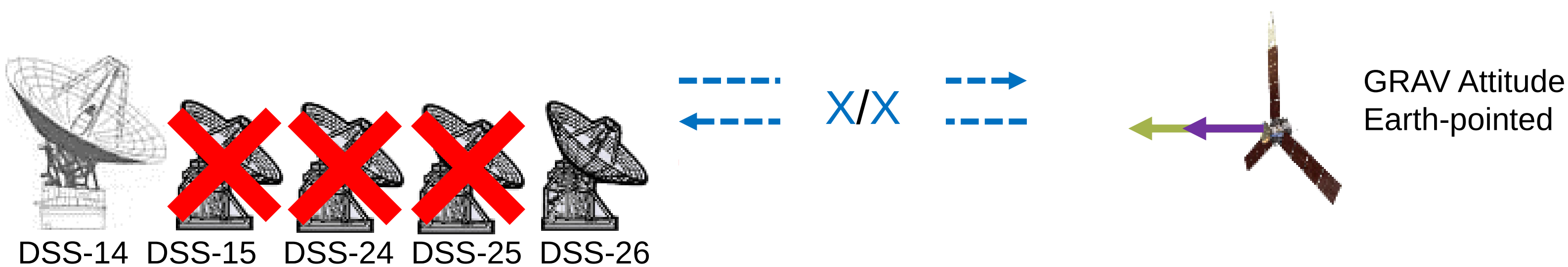
Image courtesy Tufts University

Summary of Perijoves

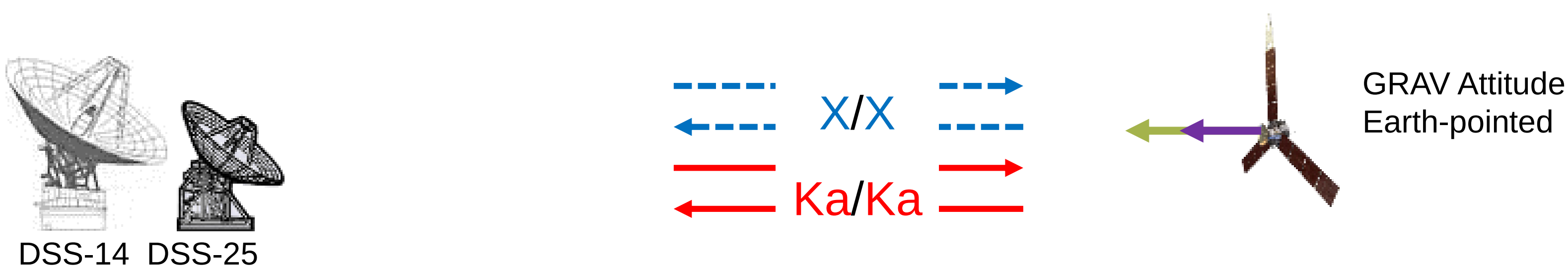
PJ-01 / August 27, 2016



PJ-02 / October 19, 2016 – Safe Mode Entry

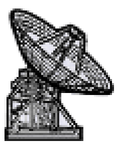


PJ-03 / December 11, 2016



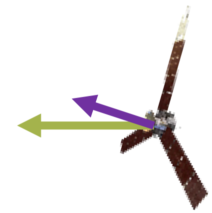
Summary of Perijoves

PJ-04 / February 2, 2017



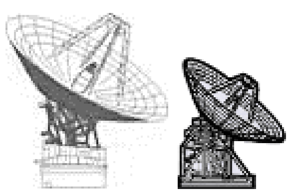
DSS-25

X/X



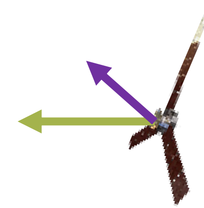
MWR Attitude
Radiometers to Jupiter
~24 deg off Earth-point
Medium Gain Antenna

PJ-05 / March 27, 2017



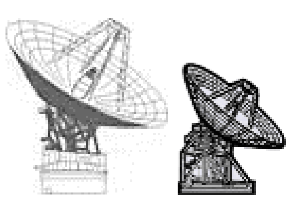
DSS-14 DSS-25

X/X



MWR-tilt Attitude
Radiometers to Jupiter
~27 deg off Earth-point
Medium Gain Antenna

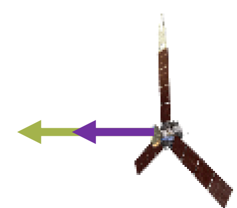
PJ-06 / May 19, 2017



DSS-14 DSS-25

X/X

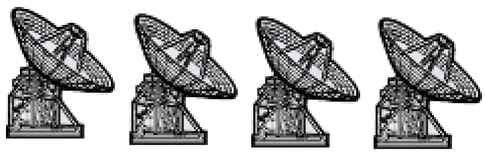
Ka/Ka



GRAV Attitude
Earth-pointed

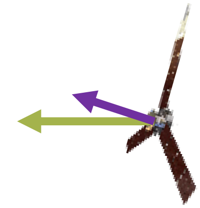
Summary of Perijoves

PJ-07 / July 10, 2017 – Great Red Spot Flyover



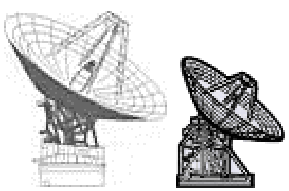
DSS-15 DSS-24 DSS-25 DSS-26

X/X



MWR Attitude
Radiometers to GRS
~16 deg off Earth-point
Medium Gain Antenna

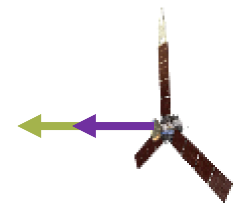
PJ-08 / September 1, 2017



DSS-14 DSS-25

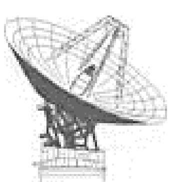
X/X

Ka/Ka



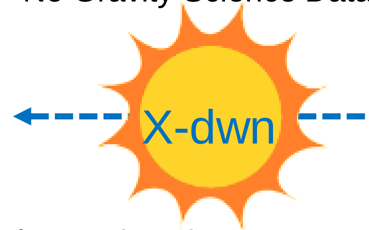
GRAV Attitude
Earth-pointed

PJ-09 / October 24, 2017

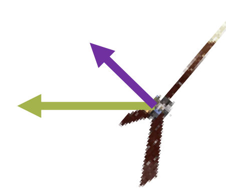


DSS-14

No Gravity Science Data



Solar Conjunction SEP ~1.9 deg

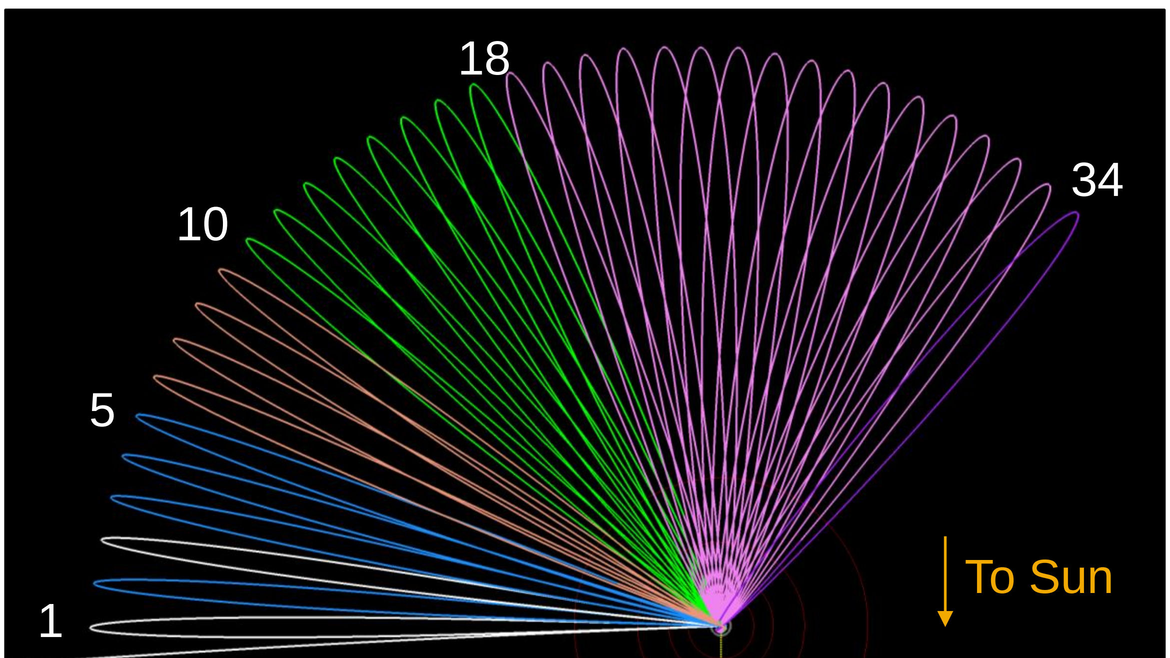


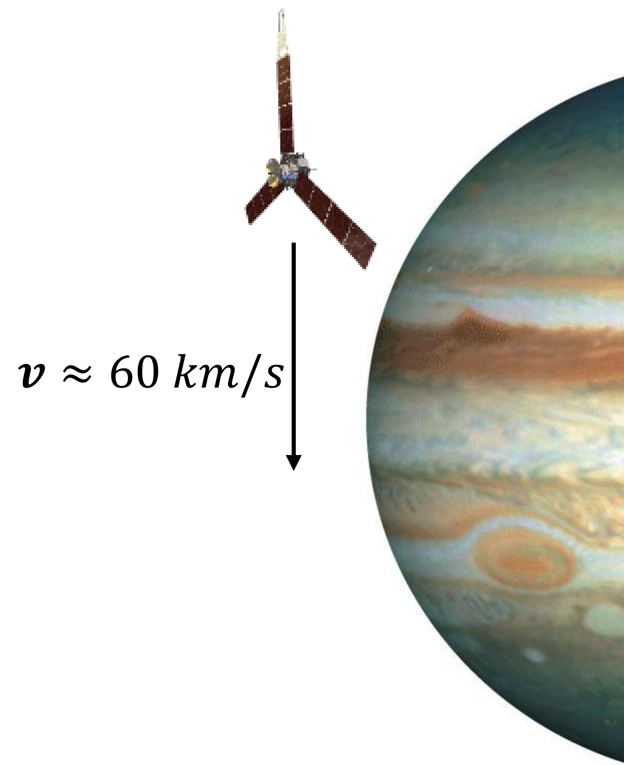
MWR-tilt Attitude
Radiometers to Jupiter
~39 deg off Earth-point
Low Gain Antenna

Considerations in Larger 53-Day Orbits

Doppler Dynamics

- Spacecraft velocity relative to ground station, projected onto the line-of-sight
- Speed at perijove about the same – but precession of orbit plane is faster



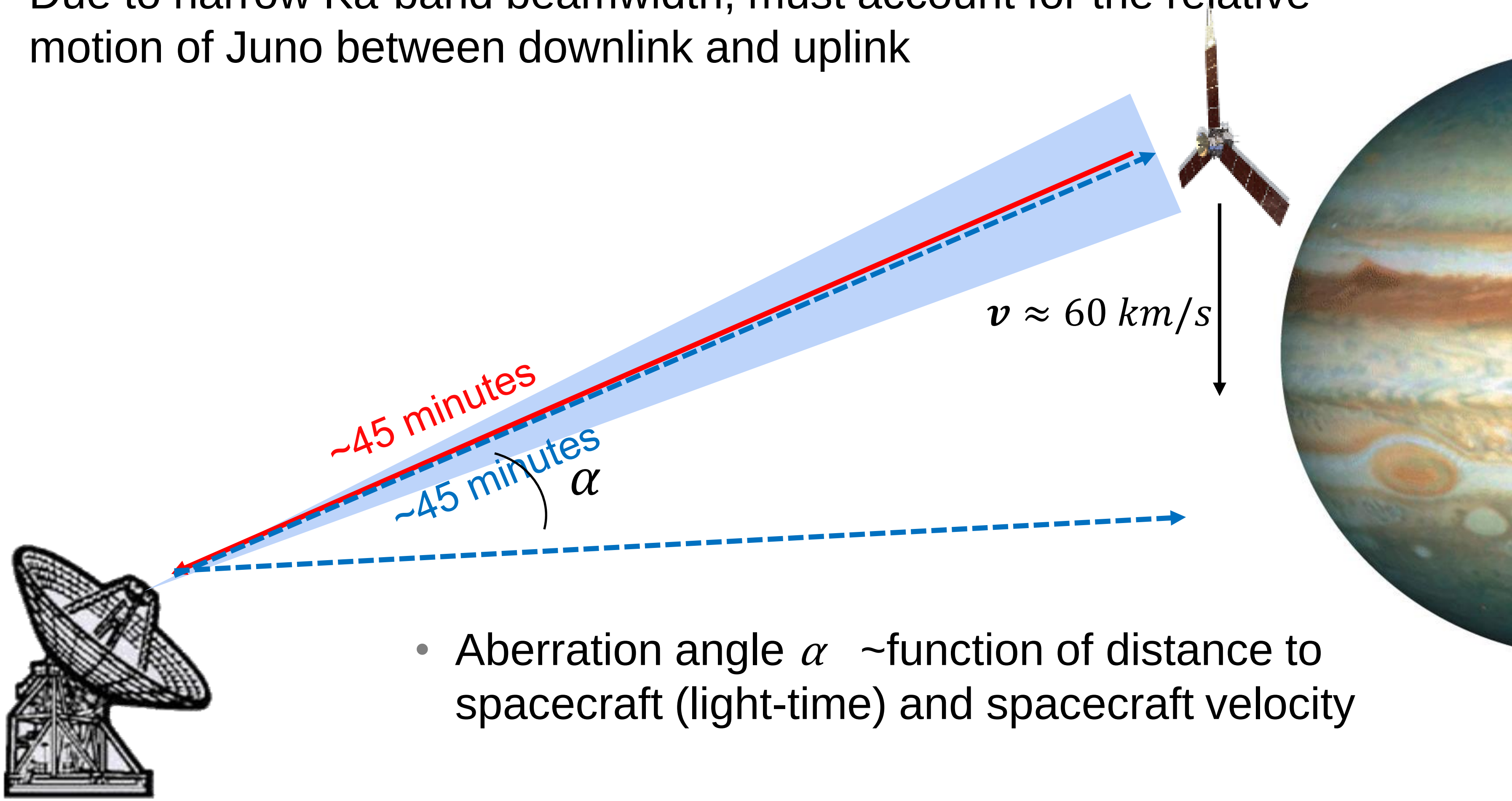


Diagrams courtesy Stuart Stephens, Juno Mission Planning

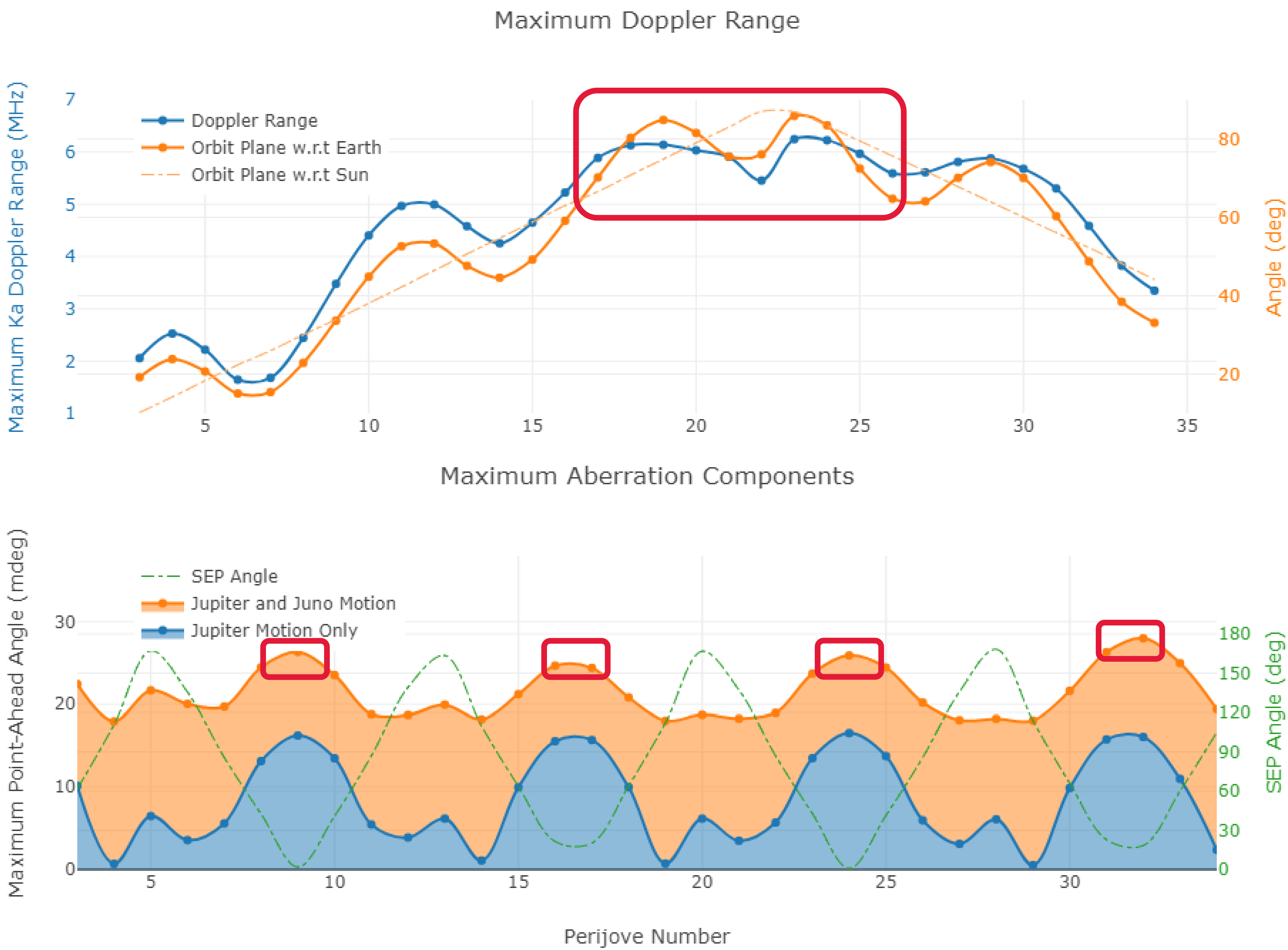
Considerations in Larger 53-Day Orbits

Ka-band Pointing & Uplink Aberration

- Due to narrow Ka-band beamwidth, must account for the relative motion of Juno between downlink and uplink



- Aberration angle α ~function of distance to spacecraft (light-time) and spacecraft velocity

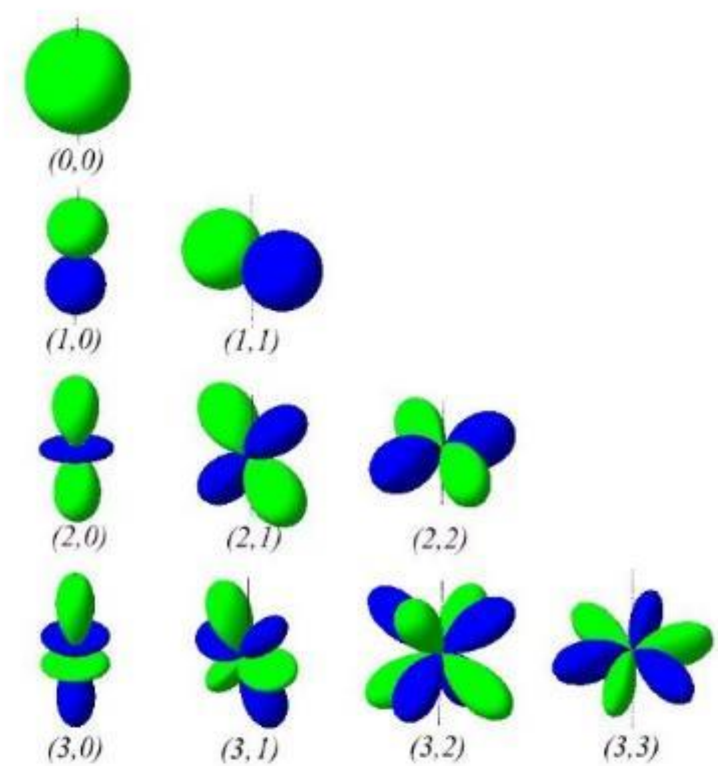


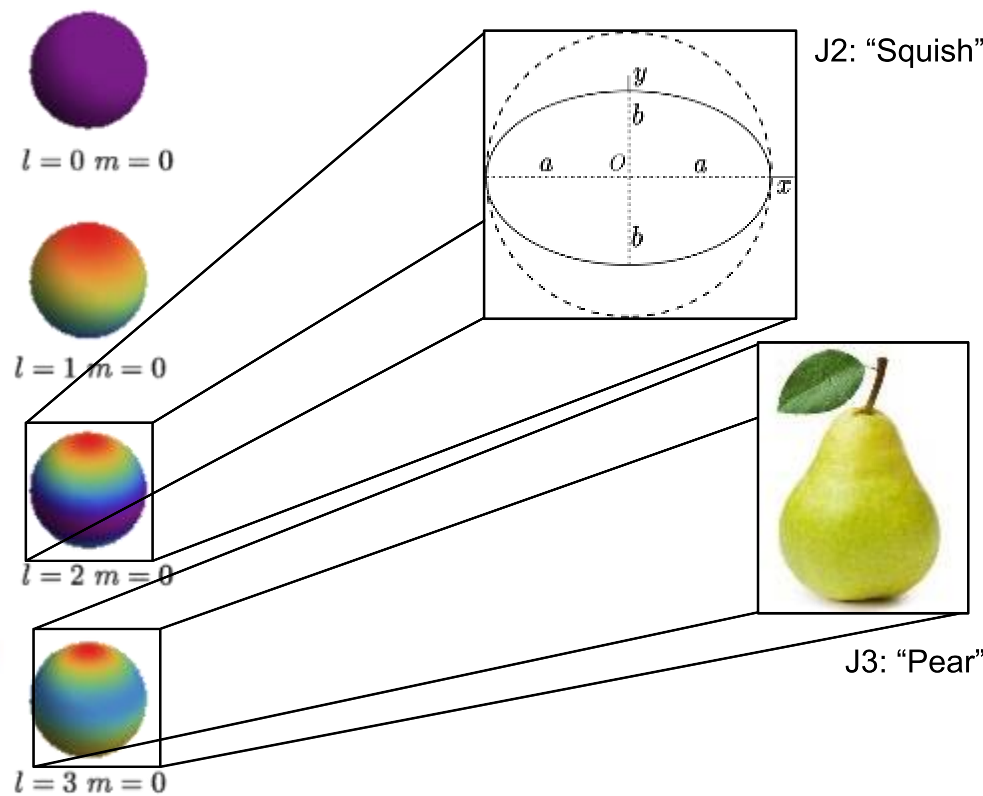
Maximum Doppler Range
Maximum Ka Doppler Range (MHz)
Angle (deg)
Doppler Range
Orbit Plane w.r.t Earth
Orbit Plane w.r.t Sun
1
2
3
4
5
6
7
20
40
60
80
5
10
15
20
25
30
35
Maximum Aberration Components
Maximum Point-Ahead Angle (mdeg)
SEP Angle (deg)
SEP Angle
Jupiter and Juno Motion
Jupiter Motion Only
0
10
20
30
0
30
60
90
120
150
180
5
10
15
20
25
30
Perijove Number

What is a “gravity field” anyway?

Gravitational Potential

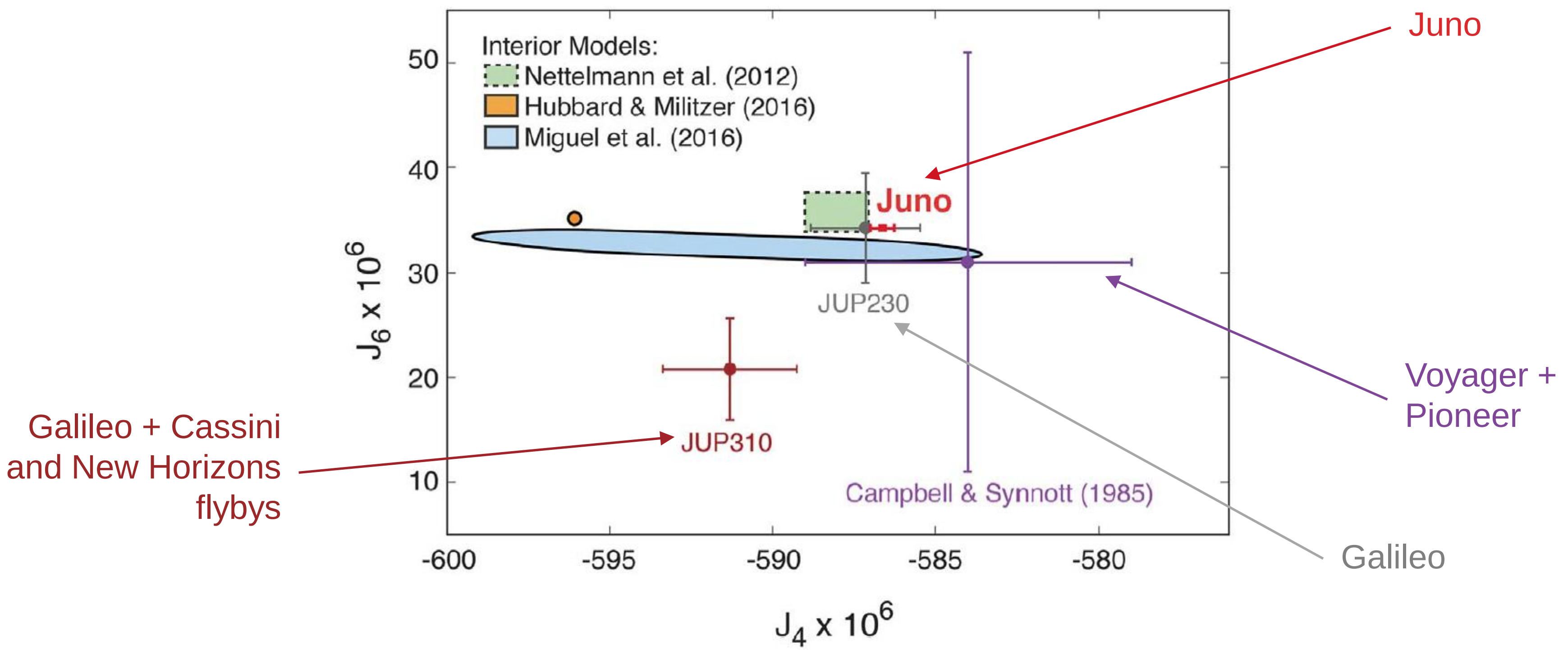
$$U = \underbrace{\frac{\mu}{r}}_{\text{Two-body}} \underbrace{- \frac{\mu^*}{r}\sum_{l=1}^{\infty}\left(\frac{a_e}{r}\right)^l P_l(\sin\phi) J_l}_{\text{Zonal harmonics}} \underbrace{+ \frac{\mu^*}{r}\sum_{l=1}^{\infty}\sum_{m=1}^{l}\left(\frac{a_e}{r}\right)^l P_{lm}(\sin\phi)[C_{lm}\cos m\lambda + S_{lm}\sin m\lambda]}_{\text{Tesseral/sectoral harmonics}}$$





Initial Results of the Gravity Investigation

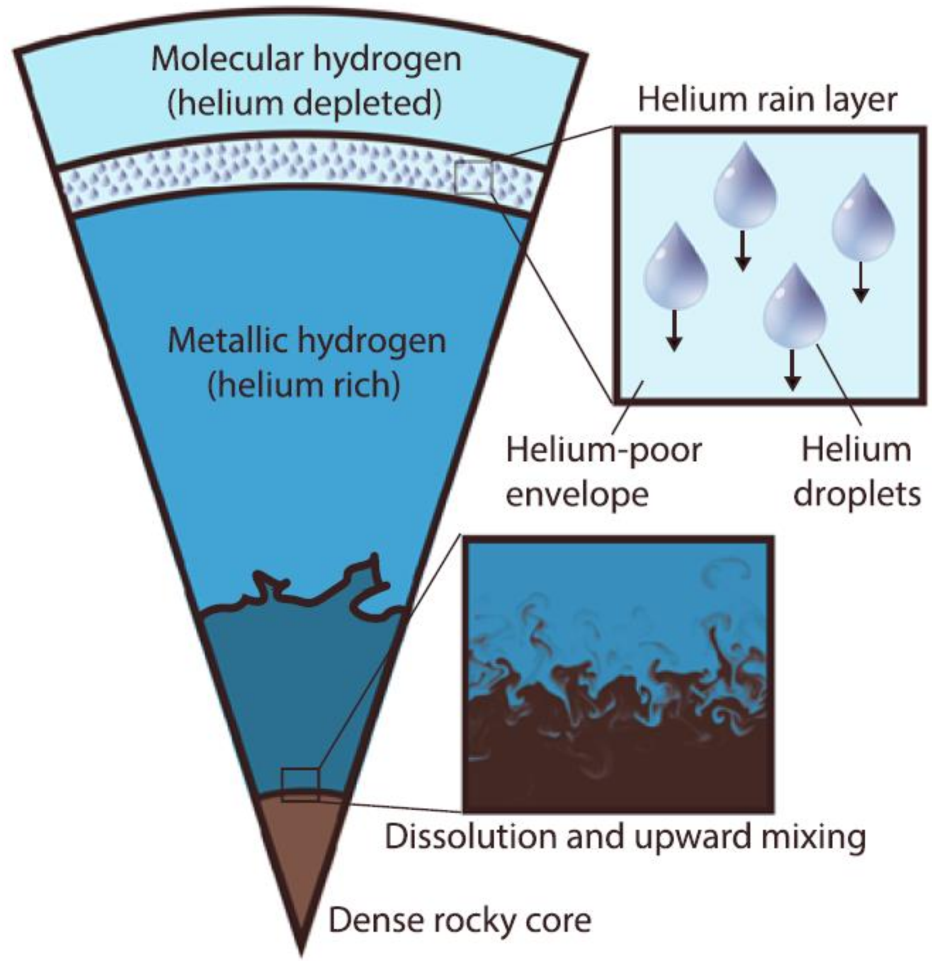
- Results from PJ-01 and PJ-02 alone improve the gravity field coefficients by a factor of 5 over previous missions
- Coefficients J4 and J6 provide strong constraints on interior models of Jupiter



Bolton et al, *Jupiter's interior and deep atmosphere,* Science 356, 2017
Folkner et al, *Jupiter gravity field estimated from the first two Juno orbits*, GRL 44, 2017

Impact on Jupiter's Interior

- Interior models prior to arrival at Jupiter do not match Juno's gravity data
- Jupiter is largely hydrogen/helium plus a concentration of heavy elements
- Current data suggest a "dilute" core of heavy elements dissolved in hydrogen may help explain Juno's measurements



Wahl et al, *Comparing Jupiter interior structure models to Juno gravity measurements and the role of a dilute core,* GRL 44, 2017

Summary & Conclusions

- Juno Gravity Science has collected good-quality gravity science data for all perijove passes, with the exception of solar conjunction
  - Medium Gain and Low Gain Antennas allowed for bonus single-band science on perijoves where the spacecraft was off-point
  - Dual-X/Ka measurements the highest precision planetary geodesy data collected between a ground station and a spacecraft

- Resulted in the highest precision gravity field of Jupiter to-date, 5x better than estimates with previous missions
- How does this impact Jupiter's interior and origin?

Acknowledgement – A Team Effort

Goldstone Deep Space Communications Complex
- DSN Antenna Operators

Lockheed Martin Space Systems Company
- Mark Susak & Chris Leeds, Juno Telecom

Madrid Deep Space Communications Complex
- DSN Antenna Operators

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- Daniele Serra

University of Bologna
- Paolo Tortora
- Marco Zannoni

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- Daniele Durante

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- Science Analysis
  - Bill Folkner, *Gravity PI*
  - Marzia Parisi
- Instrument Engineering
  - Dustin Buccino, *IOT Lead*
  - Danny Kahan
  - Oscar Yang
  - Kamal Oudrhiri
- Advanced Water Vapor Radiometer
  - Elias Barbinis
  - Meegyeong Paik
  - Scott Bryant
- DSN Systems Engineering
  - Andre Jongeling
  - Tim Cornish
- Juno Mission Sequencing & Mgmt

Southwest Research Institute
- John Anderson, *Gravity Co-I*

DSN Remote Operations Center
- DSN Network Operations Engineers

Canberra Deep Space Communications Complex
- DSN Antenna Operators

Jet Propulsion Laboratory
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jpl.nasa.gov

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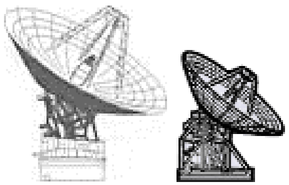
Backup slides

Summary of Perijoves

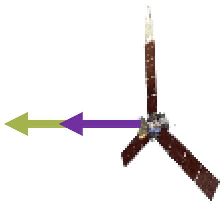
PJ-10 / December 16, 2017



DSS-14 DSS-25

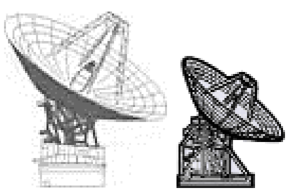
X/X

Ka/Ka



GRAV Attitude
Earth-pointed

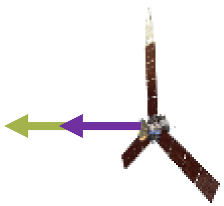
PJ-11 / February 7, 2018



DSS-14 DSS-25

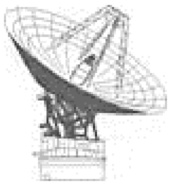
X/X

Ka/Ka



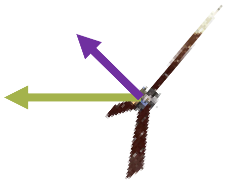
GRAV Attitude
Earth-pointed

PJ-12 / April 1, 2018



DSS-14

X/X



"+30/-20" Attitude
Optimization for Magnetosphere
~41 deg off Earth-point
Low Gain Antenna

High Dynamic Environment – Lessons Learned

- “Test-as-you fly” full instrument practice tracks
  - Upgraded/new ground hardware added after launch
  - Verify and Validate the ground hardware prior to science in the full instrument configuration

- Robust ground-based DSN configurations and adaptable instrument and telecom configuration